What are the Effects of Simulated Muscle Weakness on the Sit to Stand Transfer?

Undergraduate Thesis

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Abstract

Rising from a chair, also known as sit to stand (STS) transfer, is a common, yet challenging activity for populations that have muscle weakness, including the elderly and those with pathologies. Since this limits their mobility, experimental methods have been used to study lower-limb joint angles, torques, and muscle activations during the STS transfer to inform rehabilitation for these populations. However, rehabilitation is not 100% effective and could be improved by understanding individual muscle behavior during this task. Experimental methods cannot study this due to the complex dynamics of the human body, but dynamic simulations can and have been used to determine muscle function during the STS transfer in healthy adults; the effects of muscle weakness on this task remain unknown. This information could improve rehabilitation strategies for those who find the STS transfer difficult. The purpose of this study was to determine how muscle weakness affects the STS transfer. Experimental data were collected for six participants to generate simulations of young, healthy individuals rising from a chair to determine individual muscle forces produced during the task. Lower-limb muscles that have been found to drive the STS transfer or are commonly studied in simulation-based studies were then weakened in each model globally, in 5% decrements to 70%, and individually, in 20% decrements to 100%. Results show that the tolerable range of global weakness varies (20-60%). The STS transfer was determined to be most sensitive to quadriceps weakness. For those with muscle weakness, groups of muscles were identified as targets for rehabilitation, including the weak muscle, similarly functioning muscles, and stabilizing muscles.

Acknowledgements

First and foremost, I would like to thank Elena Caruthers for all of the support she has given me in this process. Even though she has her own, very important deadlines, she has always been willing to help me. I have learned so much from her and I am extremely grateful. I would also like to thank Dr. Robert Siston for allowing me to pursue research in his lab. He has taught me so much about research and presentation skills. I would also like to thank the rest of NMBL for supporting me with their advice and experience. Finally, I would like to thank my friends and family who have supported me as I have gone through this stressful process.

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Field of Study

Major: Biomedical Engineering

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1. Introduction

Rising from a chair, also known as the sit to stand (STS) transfer, is a common everyday task that can be challenging for some people, including the elderly and those with reduced mobility [1]. It has been found that over 60% of the elderly living in nursing homes [2] and over 6% of the elderly living independently have difficulty performing the STS transfer [3]. This is a significant problem as the STS transfer is such a common task and it is necessary to be able to perform it independently for personal mobility [1].

Many aspects of the STS transfer, such as kinetics, kinematics, and muscle activations, have been studied previously in healthy populations using experimental methods [4, 5]. One study examined how trunk kinematics impact lower limb kinetics, kinematics, and muscle activations during STS transfer since greater full trunk flexion is often used as a strategy by populations with muscle weakness. This study found that even though using greater trunk flexion during the STS transfer can reduce the knee extension moment, it does not necessarily decrease the load on the knee extensors [6]. Other studies have compared the differences in the STS transfer between healthy and pathological populations in order to help understand the movement strategies and deficits pathological populations have when performing the STS transfer. One study compared the STS transfer of healthy people and people with Parkinson's disease, as they tend to have a slower STS transfer. By observing differences between joint torques, it was determined that the likely cause of having a slower STS transfer was a reduced hip flexion joint torque, which implies that hip flexor muscle weakness may contribute to the slower STS transfer [7]. Other studies analyzed muscle activations of healthy and arthritic populations during the STS transfer; still inconclusive whether there is a significant difference between the two populations during the task [8, 9]. This suggests that there are other factors that could be responsible for how arthritic populations perform

STS transfer and make it more challenging for them. One factor could be muscle weakness, as it is known that knee osteoarthritis patients, a subset of arthritic populations, have muscle weakness in their quadriceps [10].

Furthermore, such studies have contributed to a better understanding of lower limb movements, muscle activations, and joint torques for the STS transfer, and have helped inform rehabilitation strategies [4-8]. For example, rehabilitation strategies often target muscles found to be active during the STS transfer, including the quadriceps. However, current rehabilitation strategies are not completely effective as up to 40% of knee osteoarthritis patients do not have significant improvement in short-term pain or the ability to perform everyday tasks such as the STS transfer [11]. Therefore, there is still a need to improve rehabilitation to help populations such as those with KOA improve in their STS performance. In order provide additional targets for rehabilitation, we need to understand how individual muscle behavior, including forces and activations, changes with muscle weakness since those with KOA or other pathologies often have muscle weakness [10].

While electromyography (EMG), motion capture, and ground reaction force (GRF) data are experimental tools often used to analyze the STS transfer [12, 13], they are not able to explore how individual muscle strength affects the STS transfer; they cannot isolate the forces generated by specific muscles due to the complex dynamics of the human body. However, these experimental tools can be used alongside dynamic simulations of human movement to estimate various parameters, such as muscle forces and joint reaction forces, that are difficult to measure experimentally, as well as ask "what if" questions, such as how changing muscle strength will affect other muscles during a specific motion [14]. In a previous study, Caruthers et al. used dynamic simulations to study individual muscle behavior throughout the STS transfer of a young, healthy population. The gluteus maximus, biceps femoris long head, and adductor magnus were used to lean forward and prepare to rise from the chair. The quadriceps and tibialis anterior were used to transfer momentum to lift off of the chair so the individual's center of mass was over his or her feet. Finally, the plantarflexors and all of the aforementioned muscles were used to extend the leg to get the individual into a standing, upright position. Overall, the gluteus maximus, quadriceps, and soleus were identified as the largest drivers of the STS transfer based on the amount of force they produced throughout the task [11].

While the baseline that Caruthers et al. established is useful, it is not particularly informative for populations that have weaker muscles than young, healthy populations, such as those with knee osteoarthritis [10]. We cannot assume that the results from Caruthers et al. are representative of populations who have difficulty performing the task since these populations may have different kinematics, joint torques, and muscle strengths than healthy populations, resulting in different muscle forces and muscle activations. Having a better understanding of the effects of muscle weakness on the STS transfer would allow for better targeted rehabilitation for populations with muscle weakness.

A better understanding of the effects of muscle weakness on the STS transfer could be done by using dynamic simulations. A previous study conducted by van der Krogt et al. analyzed the effects of muscle weakness during gait by using dynamic simulations. Major leg muscles and muscle groups, such as the gluteus maximus, gluteus medius, iliopsoas, hamstrings, rectus femoris, vasti, tibialis anterior, plantar flexors, gastrocnemius, and soleus, were weakened in 20% decrements both globally and individually. Gait was impaired between 40% and 60% global muscle weakness. This study also demonstrated that gait is robust to weakness in some muscles, such as the hip and knee extensors, but sensitive to weakness in the muscles that are more important in gait, which include plantarflexors, hip abductors, and hip flexors. Furthermore, as muscles were weakened, muscle activations generally increased for both the weakened muscles and those muscles that compensated for the weakness, therefore putting a larger demand on the muscles [15]. Such a study has not been performed for the STS transfer. Drawing from the methods of van der Krogt et al., the results of Caruthers at al. could be built upon by generating a better understanding of the effects of muscle weakness on the STS transfer, which could potentially help inform rehabilitation strategies for populations with muscle weakness.

1.1 Focus of the Thesis

The purpose of this study was to use dynamic simulations to determine how weakened muscles affect the STS transfer and how that weakness is compensated for by other muscles. This study was divided into two parts: global and individual muscle weakness. First, all muscles were weakened by the same interval to determine how sensitive the STS transfer was to global weakness. Then, selected muscles were individually weakened to determine how sensitive the STS transfer was to individual muscle weakness and how other muscles compensated for that weakness. While gait has been found to tolerate global weakness of 40% [15], it was hypothesized that the STS transfer would be able to tolerate global weakness up to 30% weakness before impairment since the STS transfer is generally a more difficult task than gait and requires greater joint angles, joint torques, and muscle forces [11, 16]. Furthermore, the gluteus maximus, quadriceps, and soleus were also hypothesized to be the most sensitive to weakness as they have been identified as the largest force producers during STS transfer [11]. In addition, based on van der Krogt's findings for gait [15], I hypothesized that individual muscle weakness would be compensated by increased activation of similarly functioning muscles based.

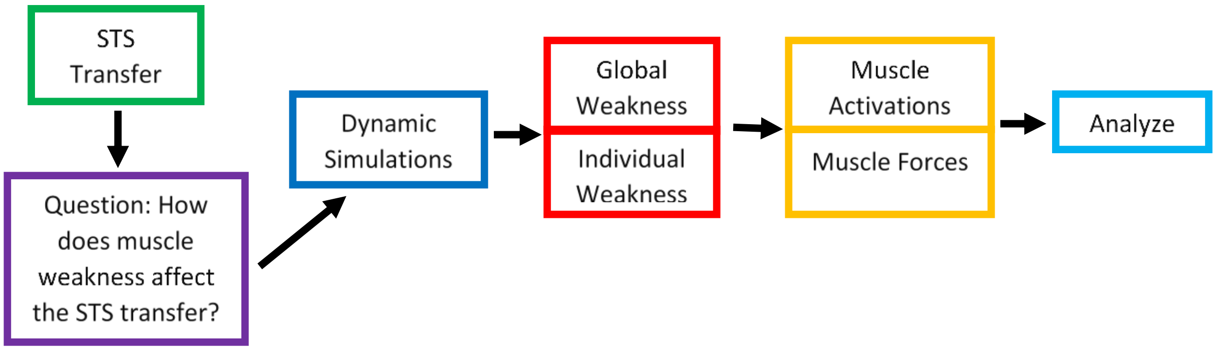

Figure 1.1: Flow chart describing the approach of the study

1.2 Overview of the Thesis

This thesis contains four additional chapters. Chapter 2 explains the methodology, including how the data was collected and how the data was analyzed using dynamic simulations. Chapter 3 provides the results of the global and individual weakness trials, including how much weakness could be tolerated and the muscle behavior due to weakness. Chapter 4 is a discussion of the results and the limitations of this study. Chapter 5 concludes this document by describing the contributions and possible future work.

2. Methodology

2.1 Data Collection

The data in this study were previously collected by a former PhD graduate student, Julie Thompson, in a study that was approved by the Institutional Review Board at The Ohio State University. Seven young, healthy participants (5 males and 2 females, age: 22.7 ± 2.9 years, mass: 78.2 ± 10.8 kg, 1.77 ± 0.06 m) were tested and analyzed in this study. Each participant performed three STS transfer trials on a hard-backed, armless chair with a seat 55.2 cm from the ground. Each trial required the participant to start by sitting at the edge of the chair with their arms crossed over their chest and both feet on two different force plates. The participants were told to stand up from the chair without moving their feet, rest for two seconds, and return to a seated position [17]. Motion capture data were collected at 150 Hz using an optical motion analysis system (8 Vicon MX-F40, Centennial, CO) to capture the movement of the reflective markers placed on the participant's body, which were arranged using the Point-Cluster technique (Figure 2.1) [18]. Ground reaction force (GRF) data were collected throughout each trial using the force plates below the participant's feet, sampled at 600 Hz (Bertec 4060-10, Columbus, OH); none were collected under the chair. Surface electromyography (EMG) data were also collected bilaterally from the gluteus maximus, gluteus medius, rectus femoris, vastus lateralis, biceps femoris, tibialis anterior, medial gastrocnemius, and soleus throughout each trial using surface electrodes sampled at 1500 Hz (Telemyo DTS, Noraxon USA, Inc; Scottsdale, AZ) (Figure 2.1). A description of electrode preparation can be found in Jamison et al. [18]. The EMG data were high-pass filtered at 10 Hz, rectified, and smoothed with a 20 millisecond window.

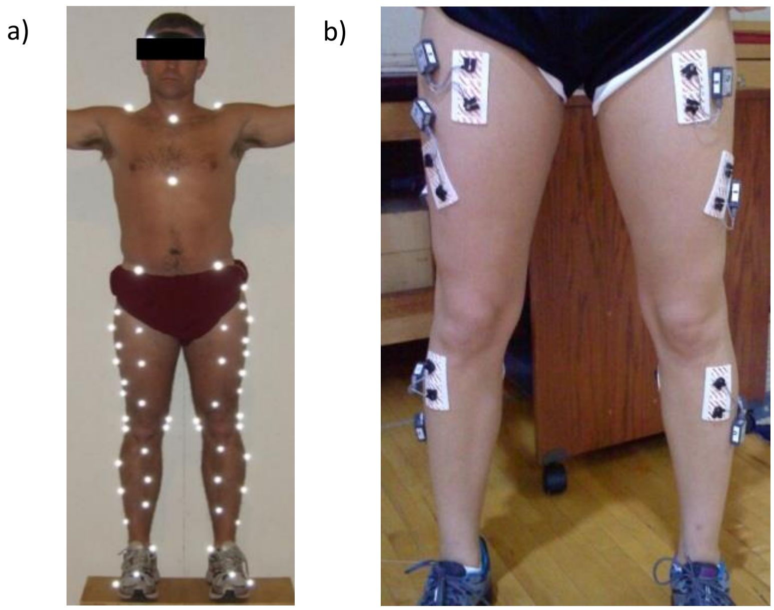

Figure 2.1: Participant data collection. a) Point-cluster technique for placing reflective markers on participants b) Surface EMG placed on muscles of interest bilaterally on a participant

2.2 Dynamic Simulations

Six of the seven participants tested (4 males and 2 females, age: 23.0 ± 3.0 years, mass: 78.6 ± 11.9 kg, 1.77 ± 0.07 m) were analyzed for this study and one STS transfer trial per participant was selected for further analysis based on how clean the motion capture data was. Dynamic simulations were created for each participant's trial using OpenSim 3.1, an open-source software package that can be used to model, simulate, control, and analyze musculoskeletal structures and their movements [19]. The generic musculoskeletal model used for these simulations, the Full Body Model 2016 (Figure 2.2), was created by research mentor, Elena Caruthers; it has a flexible lower back and arms to allow for more dynamically accurate modeling of the STS transfer. She also created baseline simulations for all participants, determining the muscle forces required during the STS transfer when no muscle weakness is present. This was achieved by first scaling the Full Body Model 2016 to each participant to match their anthropometric data. Then, inverse kinematics was solved using a least-squares approach to calculate the joint angles and translations throughout the recorded motions of each participant. Finally, inverse dynamics was run to determine joint torques across the trial based on the GRF data and joint angles calculated from inverse kinematics [11]. All of the aforementioned steps were previously performed by other members of the lab. The final step, static optimization (SO), solved for individual muscle forces and activations using the joint angles and translations from inverse kinematics and the joint torques from inverse dynamics. This step minimized the sum of muscle activations squared to optimize the simulation. This whole process can be seen below (Figure 2.3)

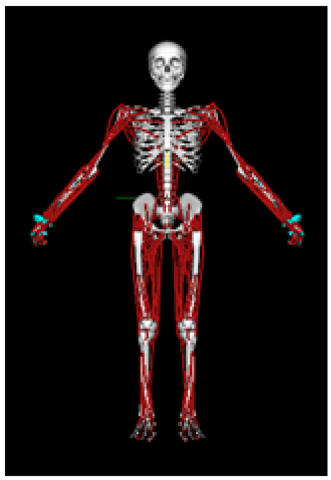

Figure 2.2: Full Body Model 2016 [11]

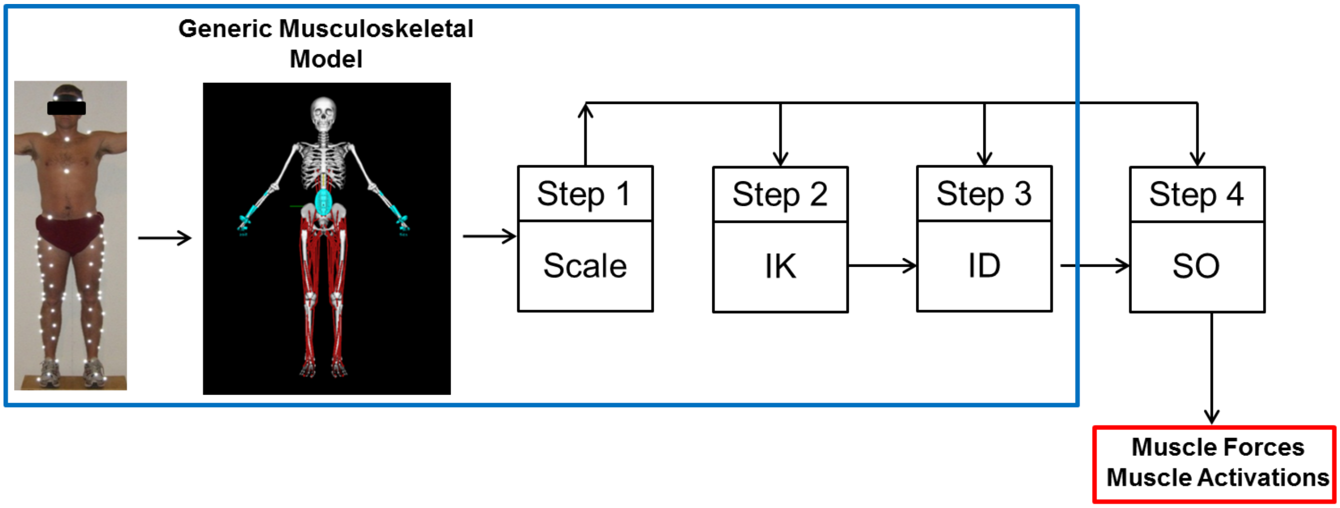

Figure 2.3: Process diagram for simulations used in this study. Everything within the blue area was done prior to this study.

From these baseline simulations, muscles were weakened both globally and individually by changing their maximum isometric force but keeping all other parameters constant [15]. The muscles that were studied individually (Figure 2.4) were the muscles of the leg that are commonly studied in simulation-based studies [11, 15], including the gluteus maximus (GMAX), gluteus medius (GMED), iliopsoas (ILPS) (comprised of the iliacus and psoas muscles), hamstrings (HAM) (comprised of the biceps femoris, semimembranosus, and semitendinosus), quadriceps (QUAD) (comprised of the rectus femoris and vasti), vasti (VAS) (comprised of the vastus medialis, vastus intermedius, and vastus lateralis), tibialis anterior (TA), plantar flexors (PLFL) (comprised of the gastrocnemius, soleus, flexor digitorum longus, and flexor hallucis longus), gastrocnemius (GAS), and soleus (SOL). Muscles were weakened in 5% increments from 0-70% both in a global weakness study and in individual groups as mentioned previously, with 100% muscle weakness defined as no muscle strength [15]. SO was then run on these weakened simulations for all levels of muscle weakness in each of the studied muscles/muscle groups for each participant.

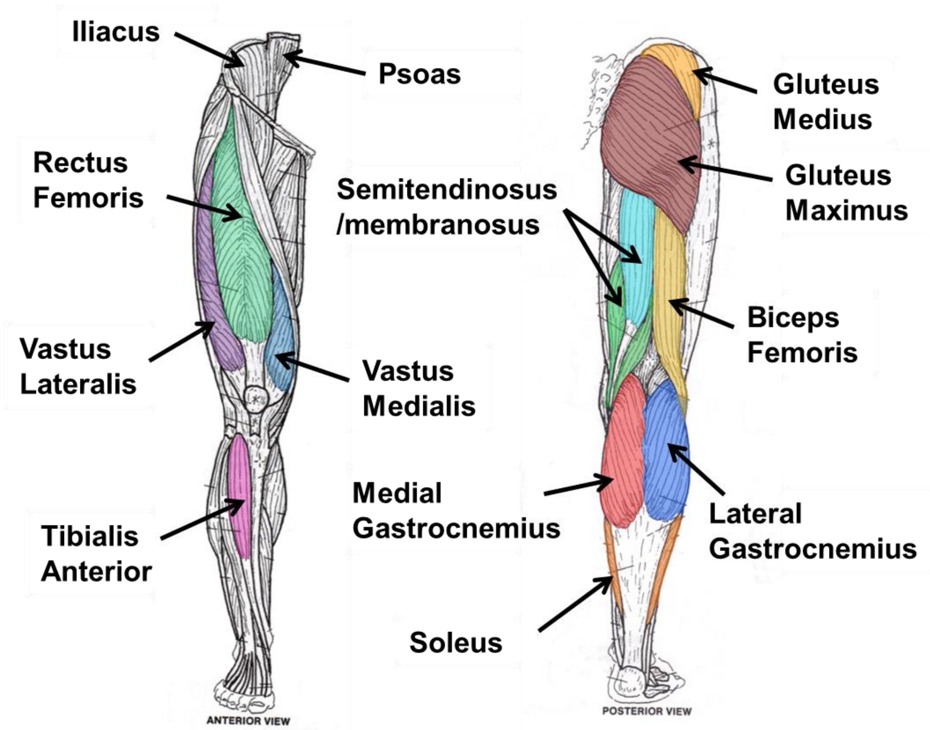

Figure 2.4: Major muscles of the leg that were weakened in individual weakness studies. Anterior view of the leg is on the left, posterior view is on the right.

To determine whether a solution to a simulation was found, all simulations were checked using failure criteria previously used by van der Krogt et al. (Figure 2.5). If 1) a solution was not found when running a simulation or 2) the reserve actuators (i.e. joint torques that augment simulated muscle forces) on any joint was more than 5% of peak joint moment, the simulation did not follow normal STS transfer kinematics and kinetics, and thus failed [15]. If the simulation passed these criteria, it could be further analyzed.

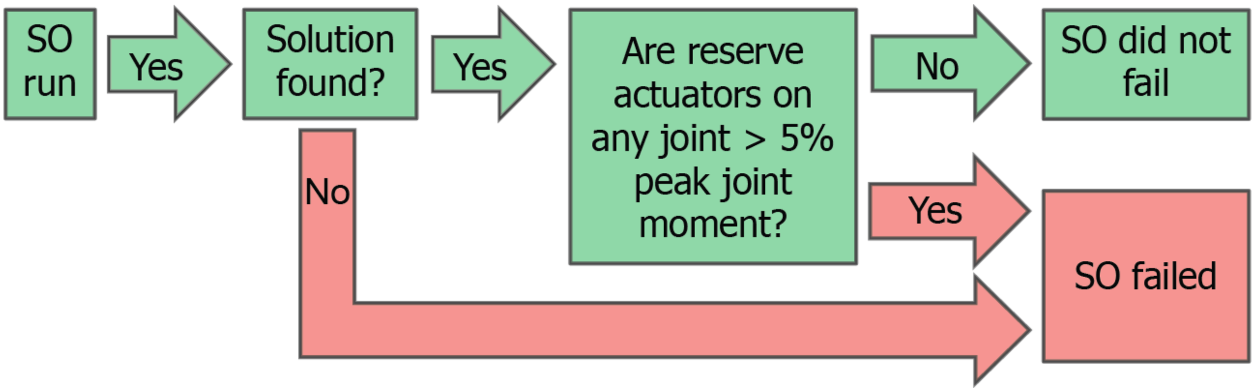

Figure 2.5: Failure criteria for determining whether a simulation failed

After muscle weakness was applied, muscle behavior changes were evaluated by 1) examining forces and activations generated in the muscles weakened, 2) examining forces and activations generated in other muscles and 3) calculating the overall demand placed on all of the muscles due to weakness integrated over the time of the action with the muscle cost formula in Equation 1, which was the same analysis that was used to study the effects of muscle weakness on walking [15].

$$\text{Muscle Cost} = \sum(\text{Muscle Activation})^2 \tag{1}$$

3. Results

3.1 Global Weakness

The amount of global weakness that could be tolerated during the STS transfer varied based on the participant (Table 3.1). The tolerable amount of muscle weakness was determined as the last simulation that could run without failing. This tolerable amount of global weakness was determined using the established failure criteria (Figure 2.5). The participants failed to perform the STS transfer between 20-60% global weakness, although three of the six participants failed before 35% weakness. Even with the variance of global weakness failures, every participant failed at the knee first, which means that the knee was always the first joint to produce an insufficient amount of moment to produce the STS transfer movement. The hip occasionally failed at the same time (two participants) or failed soon after the knee and the ankle never failed.

Table 3.1: Global weakness failure conditions for each participant.

Participant	Tolerable Weakness	Reserve Failed
1	60%	Knee
2	50%	Knee
3	45%	Hip/Knee
4	30%	Hip/Knee
5	30%	Hip/Knee
6	20%	Knee

As global weakness increased, muscles generally followed the trend of increased activation and fairly constant forces (Figure 3.1). However, the gluteus maximus, quadriceps, and occasionally the biceps femoris long head, did not follow this trend. Rather, they decreased in force, although activation may have still increased or remained constant (Figure 3.2). However, these muscles would occasionally increase in force before decreasing in force (Figure 3.3).

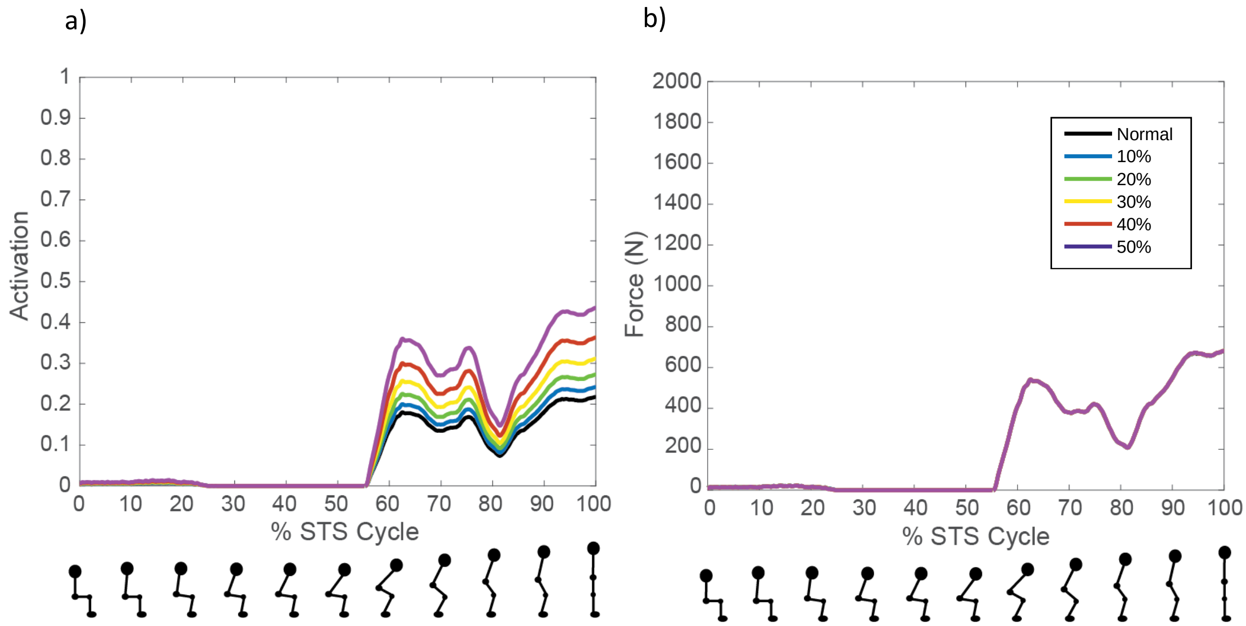

Figure 3.1: a) activation and b) force throughout the STS cycle during global weakness for SOL as an example of how muscles generally maintain constant force but increase activation as weakness increases

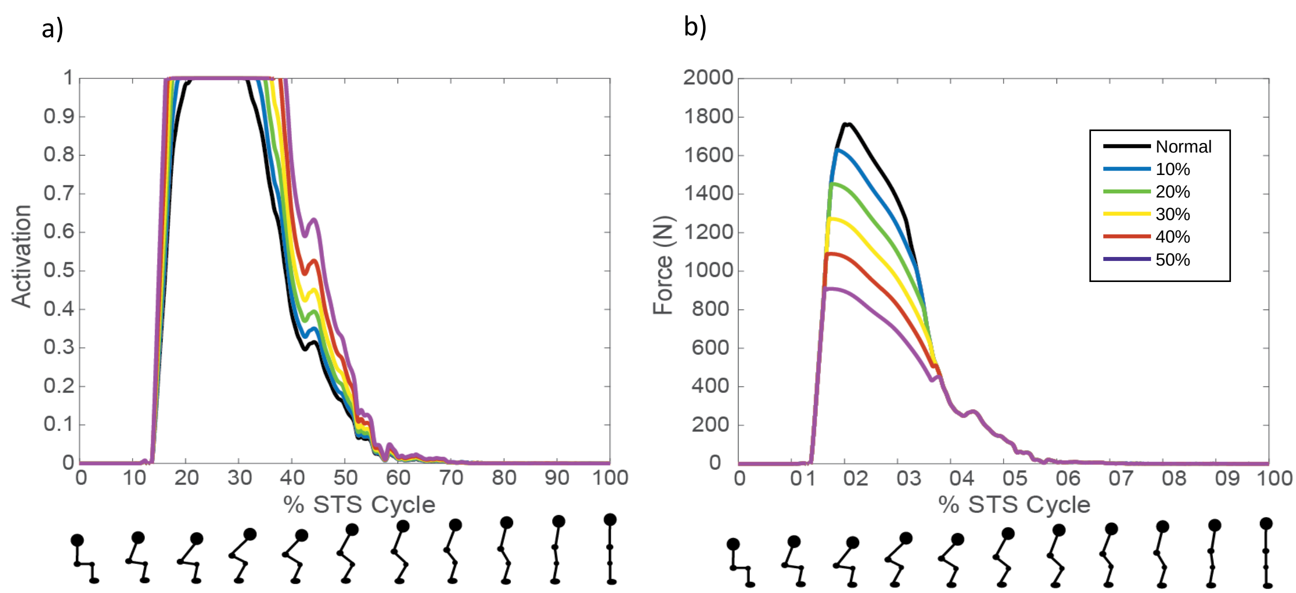

Figure 3.2: a) activation and b) force throughout the STS cycle during global weakness for GMAX for one participant.

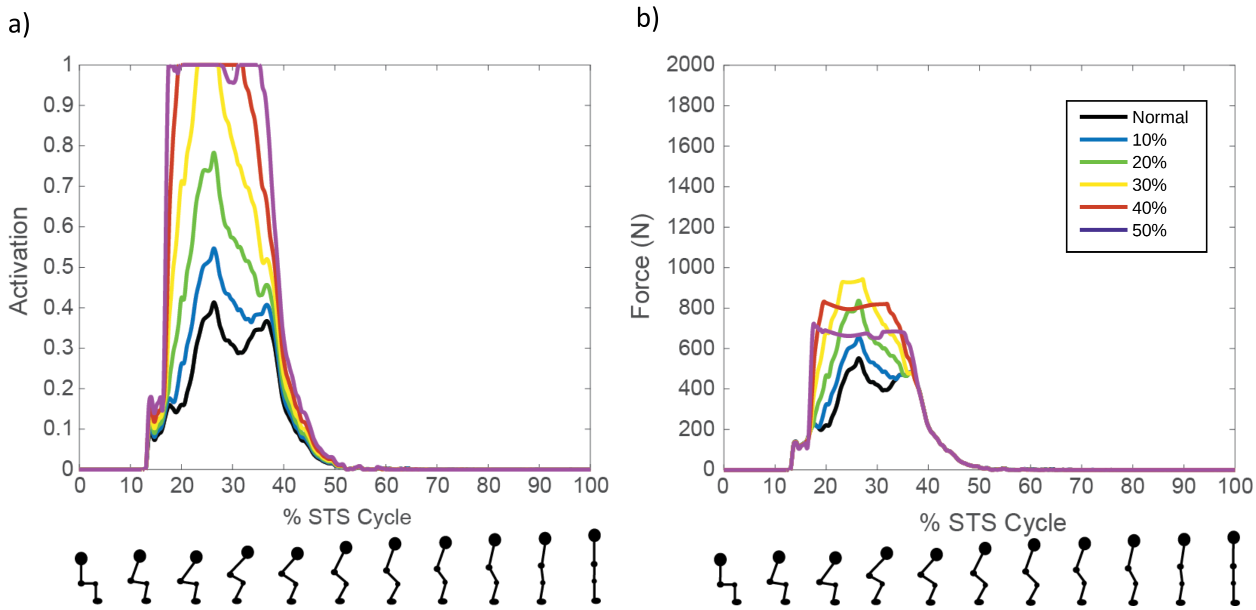

Figure 3.3: a) activation and b) force throughout the STS cycle during global weakness for BFLH for one participant. Example of when the muscle would increase in force before decreasing.

The increased muscle activations that occur with increased muscle weakness led to increased muscle cost (Figure 3.4).

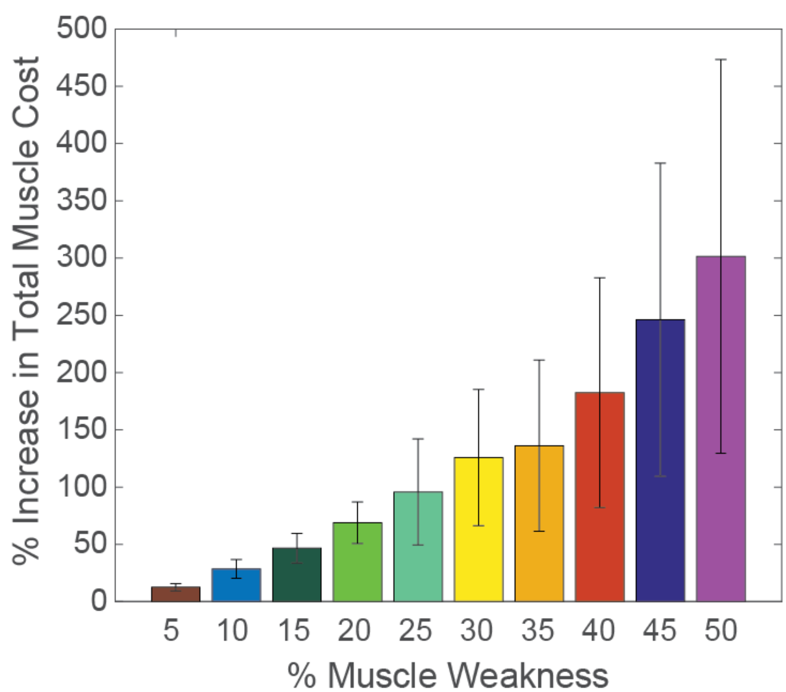

Figure 3.4: Average muscle cost as a percent increase from the baseline (0% muscle weakness) for varying degrees of global muscle weakness. Each error bar indicates ± one standard deviation

3.2 Individual Weakness

Similarly to global weakness, each individual trial was checked against the failure conditions (Table 3.2).

Table 3.2: List of when the STS transfer could not tolerate individual weakness.

Muscle	Participant	Tolerable Weakness	Joint of Failure
QUAD	1	60%	knee
	2	60%	knee
	3	40%	knee
	4	40%	knee
	5	20%	knee
	6	20%	knee
GMAX	4	80%	hip/knee
	6	60%	hip
RF	6	60%	knee
VAS	1	80%	knee
	2	100%	knee
	3	100%	knee
	4	40%	knee
	5	40%	knee
	6	20%	knee
PLFL	1	80%	ankle
	2	80%	ankle
	3	80%	ankle
	4	80%	ankle
	5	80%	ankle
	6	80%	ankle

For the muscles and muscle groups that were individually weakened, the compensators and stabilizers for that weakness were determined (Table 3.3, Table 3.4). A compensator was defined as a muscle that has the same function of the weakened muscle that increases its activation or a muscle with an opposing action to the weakened muscle that decreases its activation. A stabilizer was defined as a muscle that changes its activation to compensate for the muscle that was directly compensating for the individual muscle weakness. This included muscles that had opposing functions to compensators and increased their activations and muscles with similar functions to compensators that decreased their activations.

Table 3.3: List of compensators and stabilizers for each muscle or muscle group in the anterior leg studied in the individual weakness trials. The change in activation (increase, INC, or decrease, DEC) and muscle functions are also listed. The grey shaded boxes are only included to fill empty space in the table.

Muscle	Function	Compensator	Activation	Function	Stabilizers	Activation	Function
ILPS	HIP FLEX, LAT ROT	RF	INC	HIP FLEX, KNEE EXT	BFSH	INC	KNEE FLEX
					GAS	INC	PL FLEX, KNEE FLEX
QUAD	KNEE EXT, HIP FLEX	GMAX	DEC	HIP EXT, EXT ROT			
		ILPS	INC	HIP FLEX, LAT ROT			
		GAS	DEC	PL FLEX, KNEE FLEX			
		BFSH	DEC	KNEE FLEX			
		BFLH	DEC	KNEE FLEX, HIP EXT			

RF	HIP FLEX, KNEE EXT	BFSH	DEC	KNEE FLEX			
		BFLH	DEC	KNEE FLEX, HIP EXT			
		GAS	DEC	PL FLEX, KNEE FLEX			
		GMAX	DEC	HIP EXT, EXT ROT			
		ILPS	INC	HIP FLEX, LAT ROT			
		VAS	DEC	KNEE EXT			
		GMED	DEC	HIP ABD, MED ROT			
VAS	KNEE EXT	BFLH	DEC	KNEE FLEX, HIP EXT	GMAX	INC	HIP EXT, EXT ROT
		RF	INC	HIP FLEX, KNEE EXT	GMED	INC	HIP ABD, MED ROT
TA	DFLEX, FOOT INV	GAS	DEC	PL FLEX, KNEE FLEX			

* Functions are hip flexion (HIP FLEX), hip extension (HIP EXT), knee flexion (KNEE FLEX), knee extension (KNEE EXT), plantar flexion (PL FLEX), dorsiflexion (DFLEX), lateral rotation (LAT ROT), foot inversion (FOOT INV), external rotation (EXT ROT), medial rotation (MED ROT), and hip abduction (HIP ABD).

Table 3.4: List of compensators and stabilizers for each muscle or muscle group in the posterior leg studied in the individual weakness trials. The change in activation (INC or DEC) and muscle functions are also listed. The grey shaded boxes are only included to fill empty space in the table.

Muscle	Function	Compensator	Activation	Function	Stabilizers	Activation	Function
GMED	HIP ABD, MED ROT	GMAX	INC	HIP EXT, EXT ROT			
GMAX	HIP EXT, EXT ROT	BFLH	INC	HIP EXT, KNEE FLEX	RF	INC	HIP FLEX, KNEE EXT
		GMED	INC	HIP ABD, MED ROT	VAS	INC	KNEE EXT
HAM	KNEE FLEX, HIP EXT	GAS	INC	PL FLEX, KNEE FLEX	TA	INC	DFLEX, FOOT INV
		RF	DEC	HIP FLEX, KNEE EXT			
PLFL	PL FLEX, KNEE FLEX	TA	DEC	DFLEX, FOOT INV			
GAS	PL FLEX, KNEE FLEX	SOL	INC	PL FLEX			
		TA	DEC	DFLEX, FOOT INV			
SOL	PL FLEX	GAS	INC	PL FLEX, KNEE FLEX	QUAD	INC	KNEE EXT, HIP FLEX

* Functions are hip flexion (HIP FLEX), hip extension (HIP EXT), knee flexion (KNEE FLEX), knee extension (KNEE EXT), plantar flexion (PL FLEX), dorsiflexion (DFLEX), lateral rotation (LAT ROT), foot inversion (FOOT INV), external rotation (EXT ROT), medial rotation (MED ROT), and hip abduction (HIP ABD).

3.2.1 Iliopsoas Weakness

The STS transfer simulation did not fail due to weakness of the ILPS across all participants (Table 3.3). Muscle weakness of the ILPS was compensated by increased activation of the RF and stabilized by the increased activation of the BFSH and the GAS. Muscle cost increased with increased ILPS weakness (Figure 3.5).

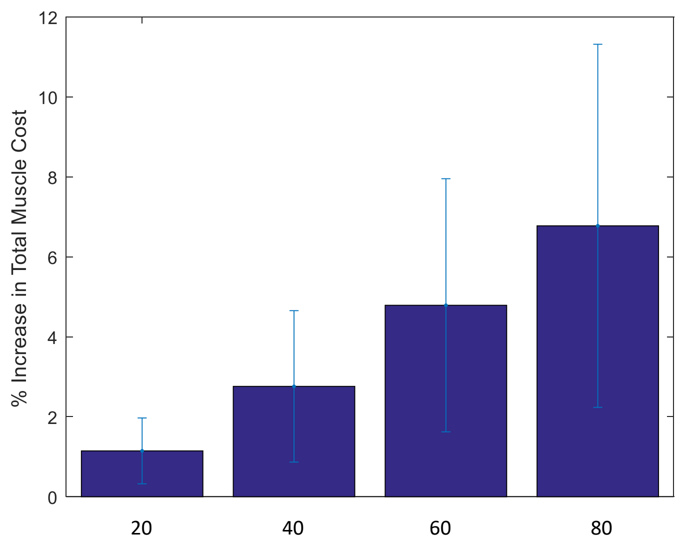

Figure 3.5: Muscle cost as a result of ILPS weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.2 Quadriceps Weakness

For these trials, all quadriceps were weakened, including the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius. All of the participants' simulations failed between 20-80% muscle weakness and at the knee joint first (Table 3.3). Muscle weakness was compensated by increased activation in the ILPS, and also decreased activation in the GMAX, GAS, and BF. There were no stabilizers determined for this muscle. Muscle cost increased with increased QUAD weakness at a highest magnitude of any other muscles studied even though 80% weakness was not considered since none of the simulations for any participant passed the failure criteria at this level of weakness (Figure 3.6).

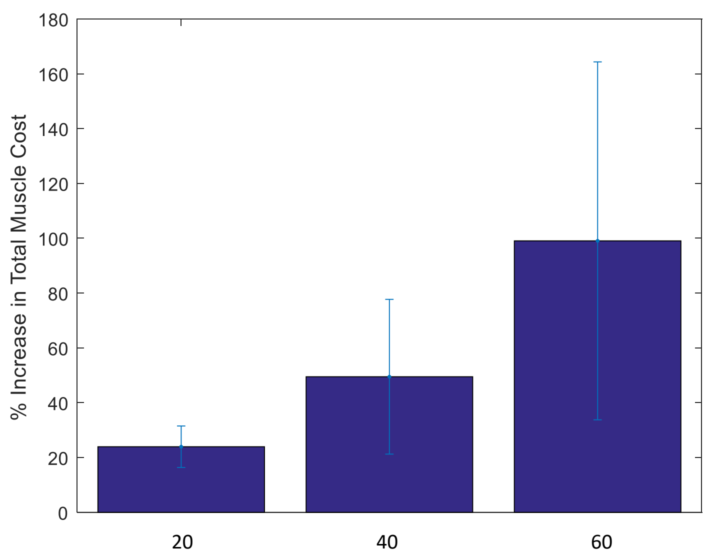

Figure 3.6: Muscle cost as a result of QUAD weakness. Each muscle cost for weakened states (20-60% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.2.1 Rectus Femoris Weakness

Only one participant's simulation failed between 60-80% muscle weakness at the knee joint (Table 3.3). Muscle weakness was compensated by increased activation in the ILPS, and also decreased activation in the GMAX, GMED, VAS, GAS, and BF. There were no stabilizers determined for this muscle. Muscle cost increased with increased RF weakness (Figure 3.7).

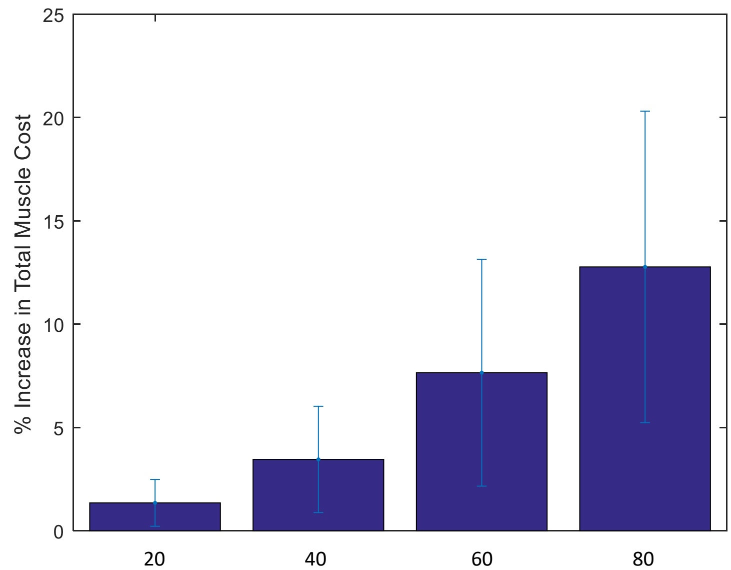

Figure 3.7: Muscle cost as a result of RF weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.2.2 Vasti Weakness

All participants' simulations failed between 20-100% muscle weakness and at the knee joint first (Table 3.3). Muscle weakness was compensated by increased activation in the RF and decreased activation in the BFLH. The weakness was also stabilized by increased activation in the GMAX and GMED. Muscle cost increased with increased VAS weakness (Figure 3.8).

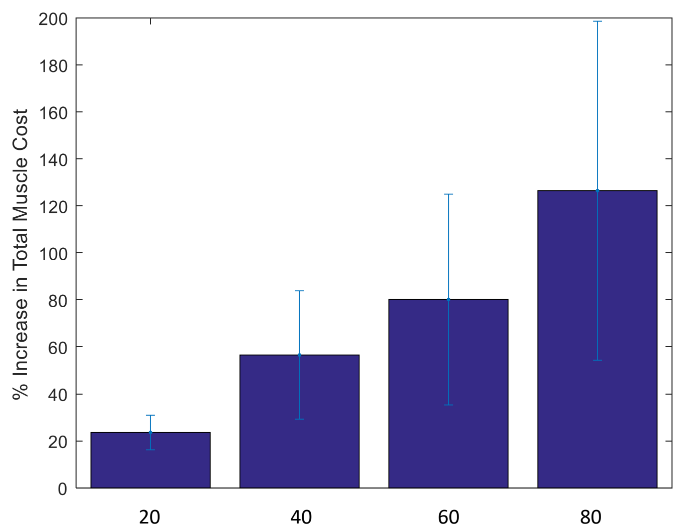

Figure 3.8: Muscle cost as a result of VAS weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.3 Tibialis Anterior Weakness

The STS transfer simulations never failed due to weakness of the TA (Table 3.3). Muscle weakness was compensated by decreased activation in the GAS. There were no stabilizers determined for this muscle. Muscle cost increased with increased TA weakness (Figure 3.9).

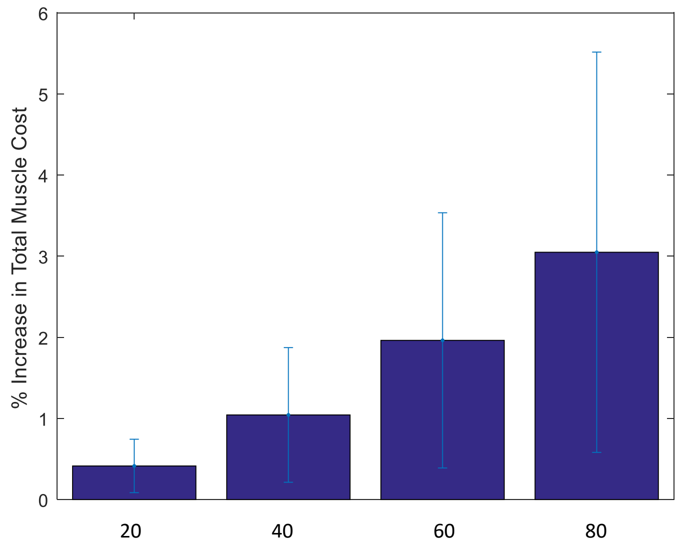

Figure 3.9: Muscle cost as a result of TA weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.4 Gluteus Maximus Weakness

The simulations for two participants failed; the first could tolerate 60% weakness at the hip joint first and the second 80% weakness at both the knee and hip joints (Table 3.4). Muscle weakness was compensated by increased activation in the BFLH and GMED. The compensators were generally stabilized by increased activation of the rectus femoris and vasti, although the rectus femoris did have decreased activation in two participants. Muscle cost increased with increased GMAX weakness (Figure 3.10).

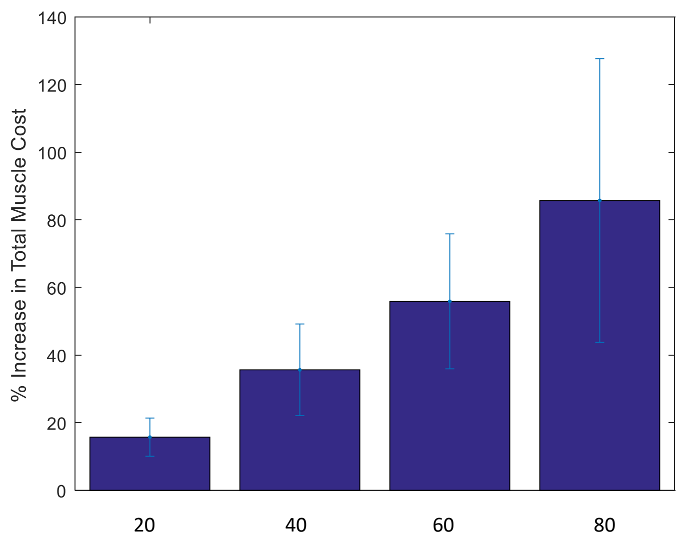

Figure 3.10: Muscle cost as a result of GMAX weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.5 Gluteus Medius Weakness

The STS transfer simulations did not fail due to weakness of the GMED across all participants (Table 3.4). Muscle weakness was compensated by increased activation in the GMAX. There were no stabilizers determined for this muscle. Muscle cost increased with increased GMED weakness (Figure 3.11).

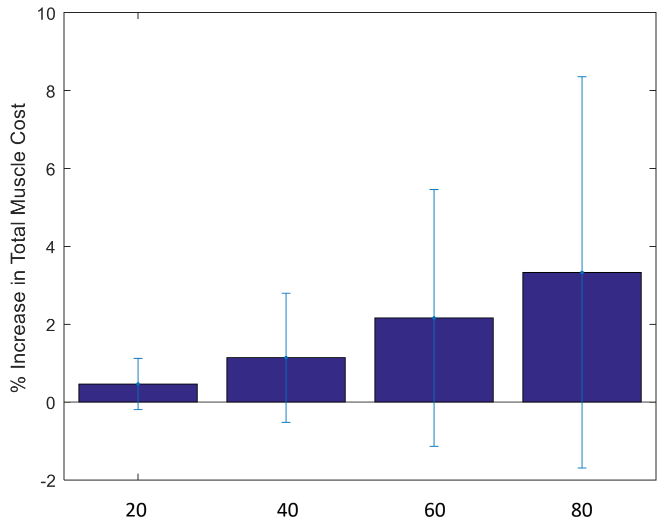

Figure 3.11: Muscle cost as a result of GMED weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.6 Hamstrings Weakness

The STS transfer simulation did not fail due to weakness of the HAM across all participants (Table 3.4). Muscle weakness was compensated by increased activation in the GAS, and also decreased activation in the RF. The stabilizer for this muscle weakness was the TA. Muscle cost increased with increased HAM weakness (Figure 3.12).

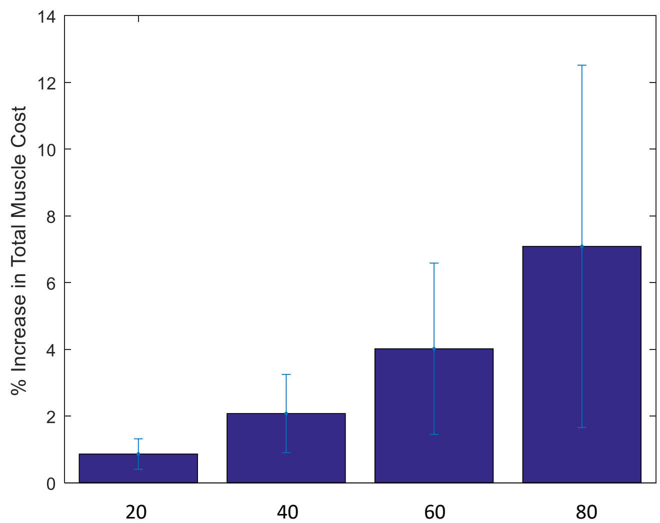

Figure 3.12: Muscle cost as a result of HAM weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.7 Plantarflexors Weakness

For these trials, all plantar flexors were weakened, including the gastrocnemius (studied individually), soleus (studied individually), flexor digitorum longus, flexor hallucis longus, peroneus brevus, peroneus longus, and tibialis posterior.. All participants' simulations could tolerate 80% muscle weakness and at the ankle joint first (Table 3.4). Muscle weakness was compensated by decreased activation in the TA. There were no stabilizers for this muscle. Muscle cost increased with increased PLFL weakness (Figure 3.13).

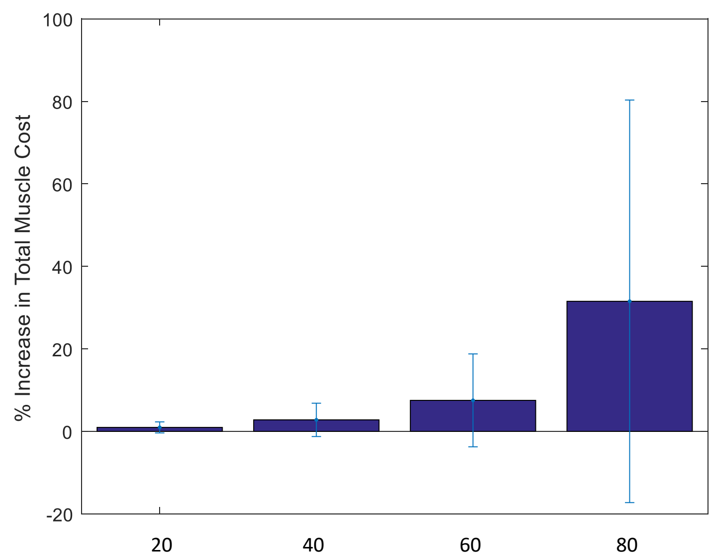

Figure 3.13: Muscle cost as a result of PLFL weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.7.1 Gastrocnemius Weakness

The STS transfer simulation did not fail due to weakness of the GAS across all participants (Table 3.4). Muscle weakness was compensated by increased activation in the SOL, and also decreased activation in the TA. There were no stabilizers determined for this muscle. Muscle cost increased with increased GAS weakness (Figure 3.14).

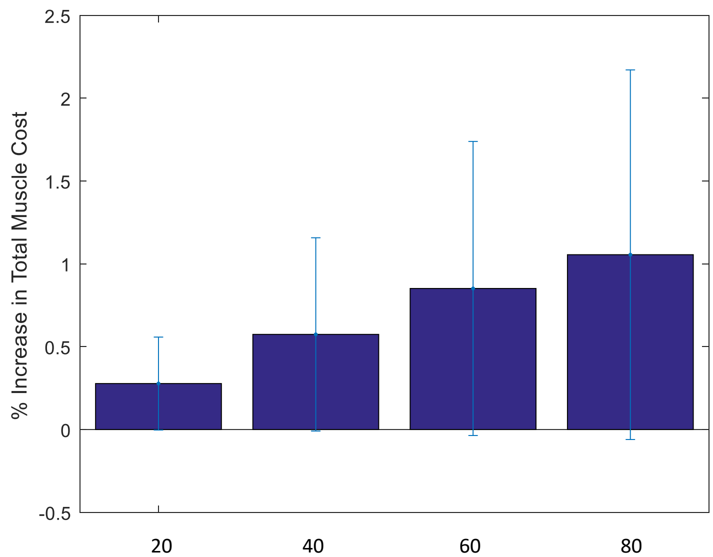

Figure 3.14: Muscle cost as a result of GAS weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

3.2.7.2 Soleus Weakness

The STS transfer simulation did not fail due to weakness of the SOL across all participants (Table 3.4). Muscle weakness was compensated by increased activation in the GAS. The weakness was stabilized by increased activation of the QUAD. Muscle cost increased with increased SOL weakness (Figure 3.15).

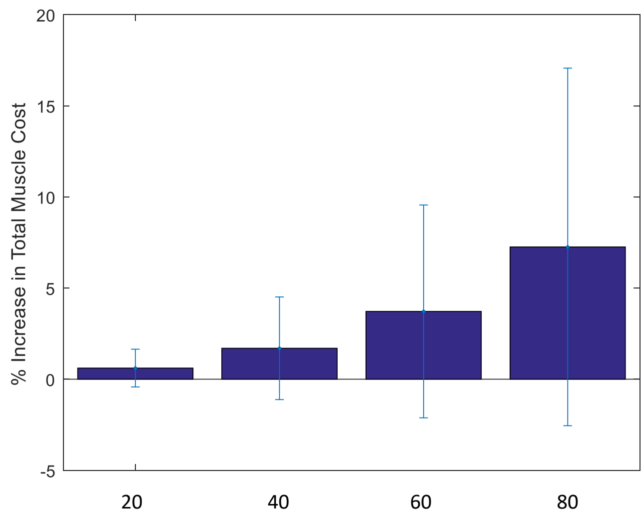

Figure 3.15: Muscle cost as a result of SOL weakness. Each muscle cost for weakened states (20-80% weakness) were plotted as a percent increase over the muscle cost of the baseline condition.

4. Discussion

This study, to our knowledge, is the first to use dynamic simulations to examine how muscle weakness affects the STS transfer. I was successful in determining how global muscle weakness affected the STS transfer and identifying muscles that compensate for individual muscle weakness. I reject my hypothesis that muscles can only tolerate 30% global muscle weakness, as the amount of weakness that could be tolerated varied from 20-65%. I also reject my hypothesis that the GMAX, QUAD, and SOL are the most sensitive to weakness. While the QUAD muscles are the most sensitive to weakness, the SOL was not sensitive to weakness and the GMAX was to an extent, but could be compensated by other muscles. Finally, I also reject my hypothesis that individual muscle weakness is compensated by increased activation of similarly functioning muscles. While this is often the case, weakness can also be compensated by decreased activation of muscle with opposite functions and by muscles that stabilize secondary muscle functions.

4.1 Global weakness

The high variability of the amount of global weakness that the STS transfer could tolerate was unexpected. The previous study that examined how muscle weakness affects gait found that global muscle weakness could be tolerated between 40-60% [15]. Since the STS transfer is generally seen as a more challenging task as it involves greater joint angles and greater joint torques, it had been hypothesized that the STS transfer would be able to tolerate only 20-40% global muscle weakness. However, the results varied between 20-60% global muscle weakness, with three participants in the hypothesized range of 20-40%, two in between 40-60%, and one between 60-65%, which tolerated even more weakness than the participants in the gait study. This high variability could be due to various factors, including different kinematics and joint torques.

When examining knee joint kinematics (Figure 4.1), those participants' simulations that failed at lower levels of global weakness were the three on the right. These three not only started decreasing in knee angle later, but did so at a greater rate, indicating a faster rotational speed. Also, the participants whose simulations failed at lower levels of global weakness tended to have higher peak joint moments, meaning that the participants whose simulations failed earlier required higher muscle forces around the knee (Figure 4.2). Therefore, there may be a connection between the amount of global weakness that can be tolerated, knee kinematics, and the peak knee joint moment during the STS transfer.

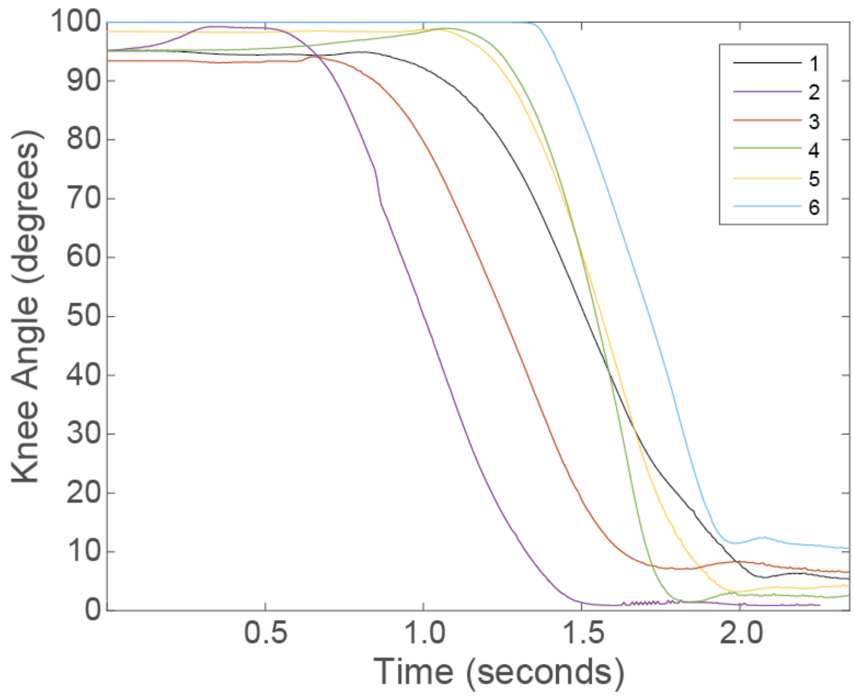

Figure 4.1: Knee angle kinematics for each participant.

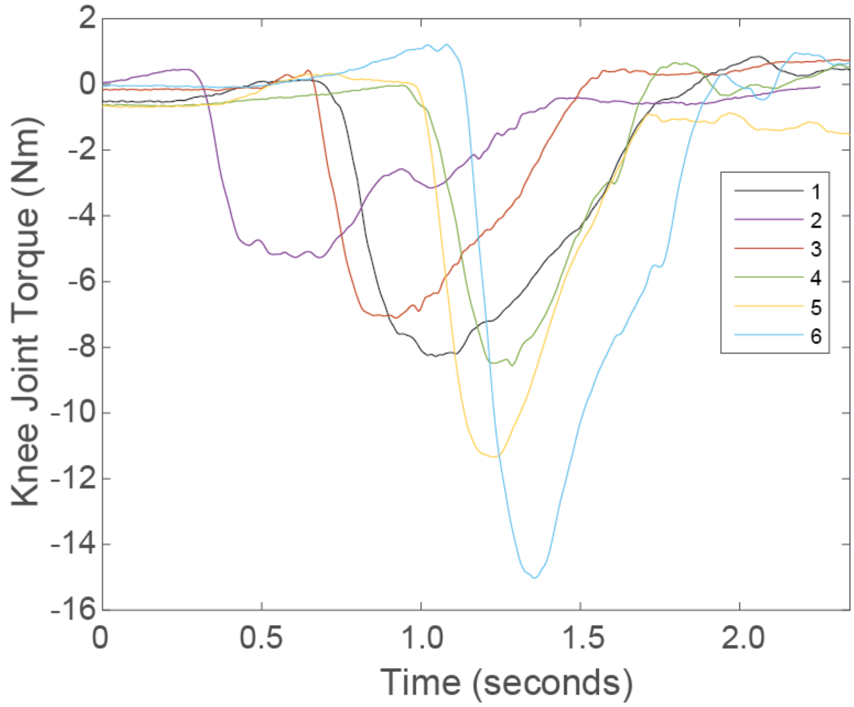

Figure 4.2: Knee joint moments for each participant.

Another interesting aspect of the global weakness portion of this study was that all simulations failed at the knee first. At each joint, the reserve actuators are checked to see if they are too large to determine if the STS transfer motion is possible given the muscle weakness. In each participant, the knee reserve actuator always was the first to meet the failure criteria (5% of peak joint torque) indicating that the muscles acting on the knee were unable to produce enough moment to perform the task before any other joint. This suggests that the STS transfer is most sensitive to weakness of the muscles around the knee.

Based on the results from this study, when muscles are weakened and the same kinematics need to be maintained, muscles either increase in activation, decrease in force, or both. Most muscles, when globally weakened, increased their activations in order to maintain a constant force. This action, while energetically more demanding, as demonstrated by the muscle cost values, allows the muscle to produce the same motion without changing the activations or forces of other muscles. However, some muscles did not follow this trend, including the GMAX, QUAD, and BFLH. Instead, they generally increased their activation and decreased in force. These muscles were highly activated compared to the rest of the muscles studied, and so it was more difficult for them to compensate for the muscle weakness solely by increasing their activations; as a result, they often decreased in force. Since the GMAX and BFLH have opposing functions to the QUAD, they had to both decrease in force in order to react to the weakness and maintain the same kinematics of the trial.

Furthermore, the increased muscle cost with increased muscle weakness was expected since most muscles increased their activation when they were weakened. The increased muscle cost with increased weakness was also consistent with gait. This illustrates that having weaker muscles induces a greater overall energy demand on the muscles, which may in turn lead to higher chance of fatigue and damage, leading to further muscle weakness and creating a downward spiral of even more weakness and compensations [15].

4.2 Individual weakness

As can be seen in Table 3.2, some of the STS transfer simulations failed due to weakness of the QUAD (RF and VAS), GMAX, and PLFL. The QUAD muscles failed the earliest due to individual weakness, which was more so represented by the VAS muscle individual weakness case. This is because there are no other muscles that function as knee extensors and knee extension is a necessary part of the STS transfer since it is needed to rise off of the chair during the STS transfer. Since no muscles could replace the role of the QUAD muscles, the weakness of these muscles severely reduced the ability to perform the STS transfer. While the RF is also used to extend the knee like the VAS muscles, there are other muscles that can perform hip flexion, such as the ILPS, and knee extension, such as the VAS, if it is individually weakened. The GMAX is also very important, as it produces large amounts of force for hip extension when lifting off of the chair during the STS transfer. However, once again, there are still other muscles that can replace its function, such as the BFLH and GMED. Therefore, only a couple of participants at high levels of GMAX weakness could not perform the STS transfer. Furthermore, since the entire group of PLFL muscles were all weakened, it was expected that the simulation failed at 100% weakness because plantar flexion is required to stabilize the leg at the end of the STS transfer. However, it is intriguing that the PLFL muscles only caused the simulation to fail at 100% weakness whereas the only knee extension muscles, the QUAD muscles caused the simulation to fail at lower amounts of weakness. This indicates that the STS transfer is more sensitive to QUAD muscle weakness since they have been determined to be some of the main force contributors to the STS transfer. This is consistent with gait since the QUAD muscles are a main driver of the STS transfer. However, the STS transfer was not sensitive to weakness of the other main force contributors, the GMAX and SOL muscles [11]. However, the GMAX and SOL functions could be performed by other muscles, while the functions of the QUAD muscles could not. This stems from the idea that the muscles to which the STS transfer is most sensitive are the main drivers of the task [15], and suggests that weakness of those muscles can still be compensated by other muscles, as long as they have similar function.

When individual muscles were weakened, other muscles had to compensate for that weakness in order to produce the same motion. Compensators could have two actions in response to weakness of another muscle: increase activation in a similarly functioning muscle or decrease activation of an opposing muscle. In addition to these compensators, muscles occasionally had to stabilize the system because the compensators introduced additional movements that had to be adjusted for. All of the stabilizing muscles identified in these trials increased in activation. The increased activations from compensators and stabilizers increased overall demand on the muscles and therefore could lead to fatigue and damage of muscles. However, having increased activations means that these muscles are possible targets for rehabilitation to help those who have difficulty performing the STS transfer task. The need for stabilizers is not favorable, however, because the ones identified for muscle weakness during this task increased in muscle activation, and therefore always increased overall demand on the muscles. Also, since stabilizers increase forces on an opposing muscle, this causes co-contraction, which could increase loads on lower extremity joints. Furthermore, when there are no other muscles that can perform the same function as the weakened muscle, as is the case for the QUAD muscles, other approaches, such as devices that aid in knee extension, should be considered.

4.3 Limitations

The limitations to this study should also be considered. Participants with muscle weakness have been shown to have different kinematics than young, healthy populations [10]. However, young, healthy participants were weakened through a simulation for this study. Each participant's simulation was fixed to the kinematic data that was recorded for that participant, even after muscle weakness was applied. Since people with muscle weakness have been shown to perform the STS transfer differently, using the kinematics of young, healthy participants may not accurately represent how muscle weakness affects the STS transfer of someone who actually has muscle weakness. The muscle cost formula used to analyze overall demand on muscles may not be the best measure. It uses the same weight for all muscles in the simulation even though some muscles are larger and therefore use more energy. This analysis also does not take into account different types of muscle fibers (fast-twitch/slow-twitch) or differences in motor unit recruitment between muscles. While these aspects should be considered, the muscle cost formula was used to be consistent with the analysis of how muscle weakness affects walking [15]. Another limitation is that this study only used six participants, although this number is similar to the number of participants used in other simulation-based studies [11, 15, 20].

5. Conclusion

5.1 Contributions

The STS transfer is a common task that many people find challenging, particularly those with muscle weakness. Previous studies have used experimental methods to investigate this task for healthy and pathological populations and have used findings to inform current rehabilitation strategies. However, rehabilitation is not 100% effective for the populations who find this task challenging, but a better understanding of the effects of muscle weakness on the STS transfer could help improve rehabilitation. Dynamic simulations were used to study these effects by weakening the simulated models generated from the STS transfer data of young, healthy participants. The results showed that there was a high variance in the amount of weakness that could be tolerated due to differences in kinematics and joint torques and that the STS transfer was the most sensitive to weakness of the QUAD muscles, which is a main driver of the STS transfer [11]. Compensating muscles were identified for each muscle or muscle group weakened individually, which can be used in rehabilitation. These muscles include those with similar functions to the weakened muscle and those that perform opposing functions to maintain the STS transfer motion. In addition, greater muscle weakness was determined to cause greater overall demand on the muscles, which implies a greater chance for muscle fatigue and damage.

5.2 Future Work

In order to better understand how muscle weakness affects the STS transfer, more participants should be studied to determine whether the results of this study hold for a larger sample size. Furthermore, one of the limitations was that this study had weakened models performing the STS transfer how a young, healthy person would, which may not be representative of how someone who actually has muscle weakness would perform the task. People with known muscle weakness should be strength tested and perform the STS transfer to determine if and how they do it differently than the weakened simulations of young, healthy participants of this study. This study also identified muscles that can be targeted for rehabilitation based on certain muscles being weakened. The groups of muscles suggested for rehabilitation based on muscle weakness should be tested to determine whether they are usable in clinical practice. However, some weakened muscles do not have similarly functioning muscles that can compensate for them, and therefore external means should be considered when there is weakness in these muscles. In this case, other, external means should be considered to improve the ability to perform the STS transfer, such as a device that will perform the function of the weakened muscle. Finally, the methods of this study can be applied to other tasks, such as stair ascent and descent, to determine how muscle weakness affects them.

5.3 Summary

Dynamic simulations were used to determine how muscle weakness affects the STS transfer. We determined the level of global and individual muscle weakness that could be tolerated for several muscles, the muscles to which the STS transfer was most sensitive, and the muscles that compensate for weakness. Understanding this information could lead to improved rehabilitation strategies for people who have difficulty performing the STS transfer.

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